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DIGITAL RECORDING USING HOLOGRAM ARRAYS: some initial experiments in 100 Mbit/s recording

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Summary

The construction of an experimental holographic recorder has advanced sufficiently to carry out some initial experiments and to obtain some sample recordings of hologram tracks written on continuously moving photographic film. The hologram exposures and data transfer rates were commensurate with those values required for digital television recording. Careful analysis of the reconstructed hologram images from the test recordings has revealed some problems associated with the film and its processing for this application. The results have also directed attention to several critical areas of the proposed system and underlined the deficiencies still remaining in the principal transducers such as the page-composer and the digital light-deflector.

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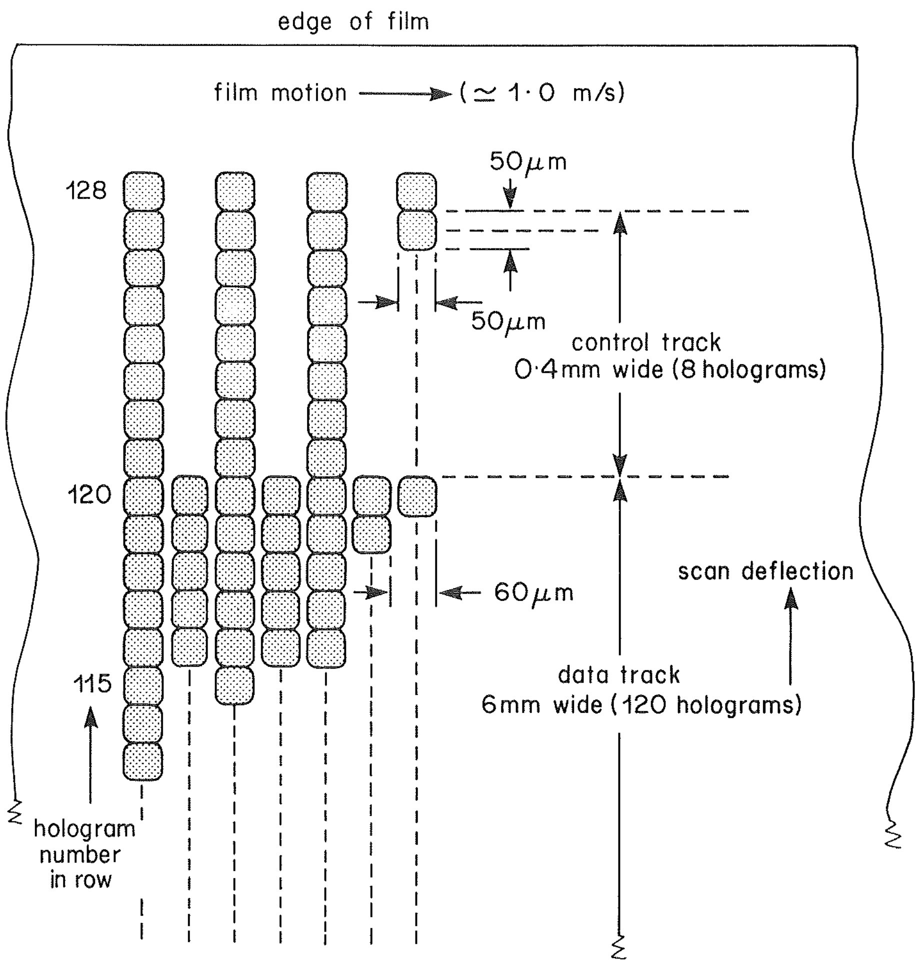

Fig. 1 - Micro-hologram array format proposed for complete 100 Mbit/s recorder

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1. Introduction

From the results of earlier experiments with micro-holograms[1] and from a study of methods for modulating and deflecting laser beams,[2] it appeared that an optical system[3] using hologram arrays would be feasible for recording digital television signals. Since then, work has continued with the aim of verifying the feasibility of this method by constructing an experimental recording and replay system using low-power lasers as sources and photographic film as the recording medium. No attempt has been made to exploit the full potential of this method of recording in terms of storage density which, theoretically, is greater than 10^7 bits/cm^2. Moreover, it was intended that the initial recordings would be only partially-populated with data and that the test apparatus, when completed, would be capable of recording and replaying only a small fraction (one eighth, say) of a complete television picture. It was believed to be essential, however, that the transducers which were constructed for the partially-populated experiments should operate satisfactorily at the maximum bandwidths which are required when recording a complete (fully-populated) picture, for which a nominal data transfer rate of 100 Mbit/s has been assumed.

Details of the system design concepts and the development of the principal transducers required are given in two companion Research Reports.[4,5] Prototype versions of these transducers were constructed and assembled on a laboratory test-bed, including a film transport mechanism, to form the experimental recorder.

Several initial experiments designed to explore the basic features of the system and assess the performance of the apparatus were carried out. Descriptions of these limited investigations, including some observations and the practical difficulties which were encountered, are given in this Report. Recovery of data from moving film has not yet been attempted so that measurement of the dynamic error rates, or assessment of the servo-control arrangements proposed for synchronising the replay scanning beam,[4] have not yet been obtained.

2. System parameters

In this Section the basic features of the recording system are briefly described; a full description is given in Ref. 4.

2.1. Format

In a complete recording, micro-holograms will be exposed sequentially on moving film to form the array pattern shown in Fig. 1. The micro-holograms are approximately 50 μm square and each one contains 50 bits of information. They are arranged in rows of 2^7 (128) running across the film, i.e. at right angles to the film motion (approximately). It is proposed that the last eight holograms in alternate rows are suppressed to form a control track, 0.4 mm wide, for synchronising the film with the scanning beam during replay.[4] The array thus forms a track 6.4 mm wide and two such tracks could be accommodated on 16 mm cine-film. For a data-handling rate of 10^8 bits/second, each 50-bit hologram must be exposed in less than 500 ns. The minimum film speed is 0.78 m/s at a packing density of 2 x 10^6 bits/cm^2; this is increased to 0.94 m/s if a guard band of 10 μm between rows is included as shown in Fig. 1.

In the partially-populated version of the recorder, the exposing beam is deflected only over a limited scan of hologram positions in each row. The deflection rate is the same as for the complete system, i.e. 2 holograms/μs, but the exposing spot is dormant for the remainder of the scan period.

2.2. Recording

The arrangement used in the experimental recorder is shown in Fig. 2(*a*). The laser source is a 10 mW, helium-cadmium (He-Cd), continuous-wave (c.w.) gas laser which emits plane-polarised blue light at a wavelength of 441 nm. The beam is split by a partially-reflecting mirror to derive a reference-beam and a signal-beam. The signal-beam is expanded and 50 digit-beams are derived which are independently modulated (switched) by a 50-port page-composer. Each port of the

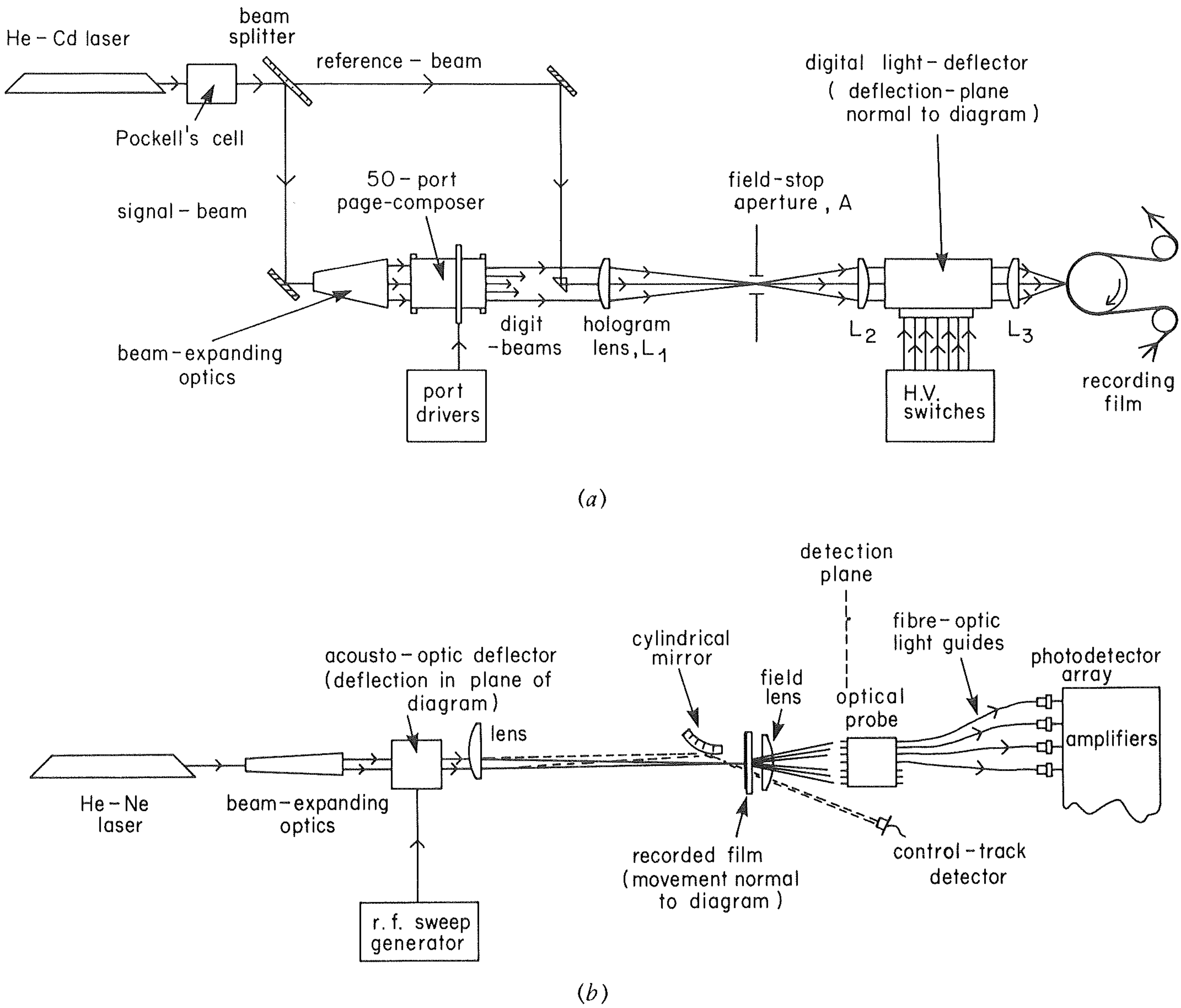


Fig. 2 - Basic system used in the experimental recorder

(a) recording arrangement (b) replay arrangement

page-composer can handle a 2 Mbit/s data stream; thus by parallel operation of all ports a total rate of 100 Mbit/s is available. The digit-beams and central reference-beam together form a two-dimensional array of parallel beams which, after passing through a digital light-deflector, are brought to a focus at the film plane to form the micro-hologram. The maximum numerical aperture of the recording system is 0.16 and the spatial-frequency band is from 50 to 380 cycles/mm. The deflector has a resolution of 2^n output positions, where n is the number of stages, and deflects in a single plane normal to the film motion. The maximum deflection rate required is two spots (i.e. hologram positions) per microsecond.

2.3. Replay

Fig. 2(*b*) shows the arrangement used for recovering the digital data in the initial experiments. The replay laser source is a 5 mW, helium-neon (He-Ne), c.w. laser emitting unpolarised red light at a wavelength of 633 nm. The laser beam is slightly expanded and after passing through an acousto-optic deflector is focused on the processed film to interrogate the hologram rows. The reconstructed 'page' of digit-beams is intercepted by an array of optical fibres each terminating, at the other end, in a photodiode which is coupled to a low-noise amplifier.

The scanning spot is approximately 50 μm in

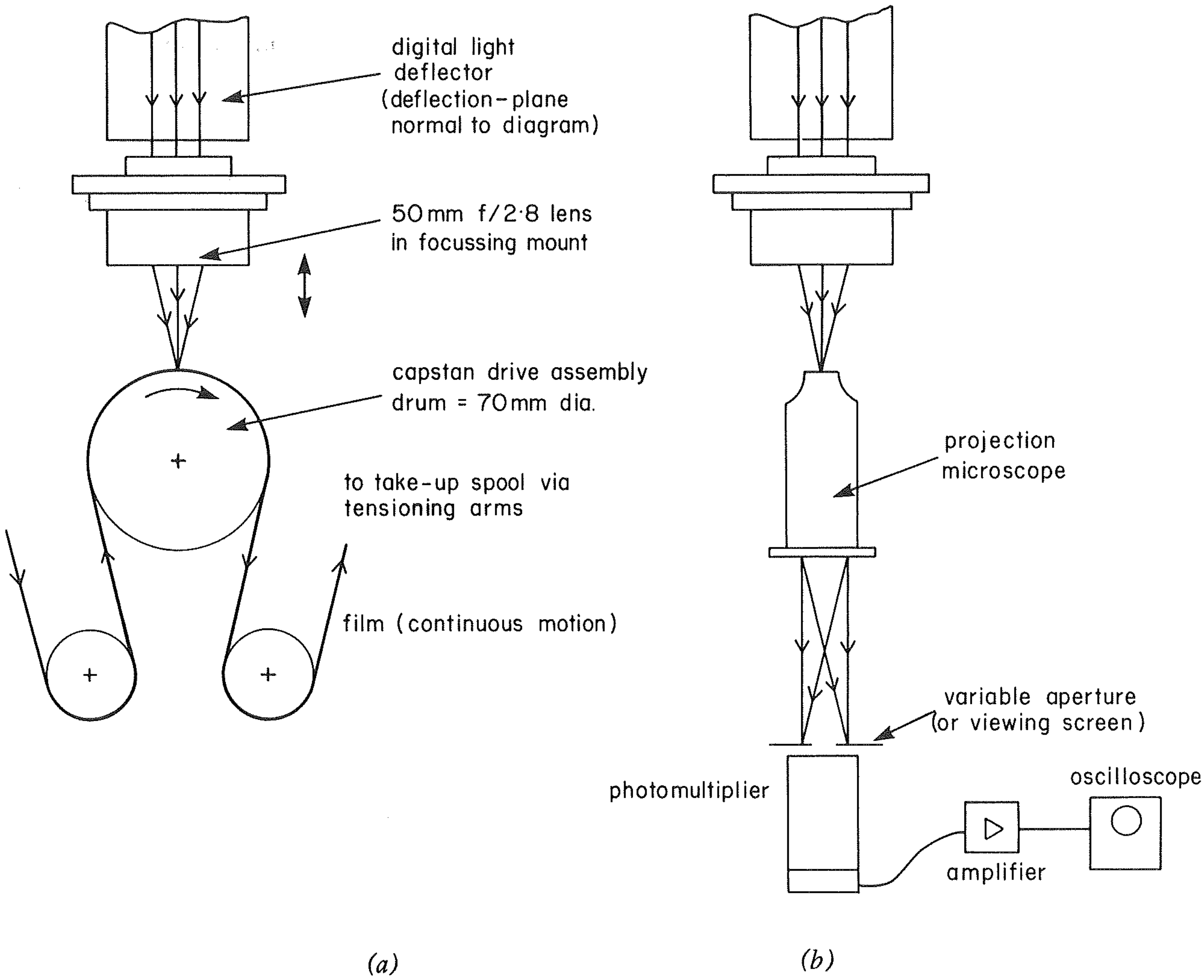


Fig. 3 - Recording head arrangements for
(a) film exposure (b) optical alignment

diameter and scans a row of holograms at two holograms per microsecond (i.e. the data transfer rate is 100 Mbit/s).

In the partially-populated version, the spot scans over approximately 24 holograms at the full rate (2 holograms/μs) but then rests for the remainder of the scan period. The scanning beam has a Gaussian radial intensity profile and its effective numerical aperture is less than 0.001.

3. Test recordings

3.1. Exposure, focus and alignment

The recorder has a reel-to-reel film transport mechanism which includes a servo-controlled capstan drive and automatic film-tensioning arms. The capstan drum is approximately 70 mm in diameter and the hologram spot is focused on the film which is in contact with the capstan, as shown in Fig. 3(*a*). For all the experiments reported here, the recordings were made by wrapping a strip of unexposed film around the capstan drum and rotating it at a constant speed. The exposure time was limited to the period of one revolution of the capstan by a mechanical shutter so that multiple exposures were prevented. After exposure, the test strip ($\simeq$ 200 mm long) was removed for chemical processing.

In order to align the optical system and to measure the parameters of the exposing beam, prior to making a test recording, the projection arrangement shown in Fig. 3(*b*) was used. The capstan assembly was removed and a projection microscope fixed in its place. By this means, an enlarged image of the exposing hologram spot was projected either on to the end face of a photomultiplier tube for radiometric measurements or on to a white screen for direct viewing. The output of the photomultiplier was amplified and coupled to a wide-band oscilloscope so that

the optical switching waveforms and the relative intensities of the reference and signal-beams could be monitored.

The setting-up and optical alignments required to obtain the optimum uniformity and maximum intensity of the exposing spot were rather time-consuming but, once achieved, could be held for periods of up to one hour. The principal difficulty was attributed to mechanical creep in the mirror adjusting mounts, especially for the reference-beam path where the alignment was critical. No trouble was experienced from environmental vibration, largely because of the short exposure times and the relatively low spatial-frequency bandwidth of the system.

Focus adjustment was obtained by an axial displacement of the final lens of the system (see Fig. 3(*a*)); the measured tolerance was ±25 μm. It was found that the capstan assembly could be removed and replaced without any need to re-adjust the focus.

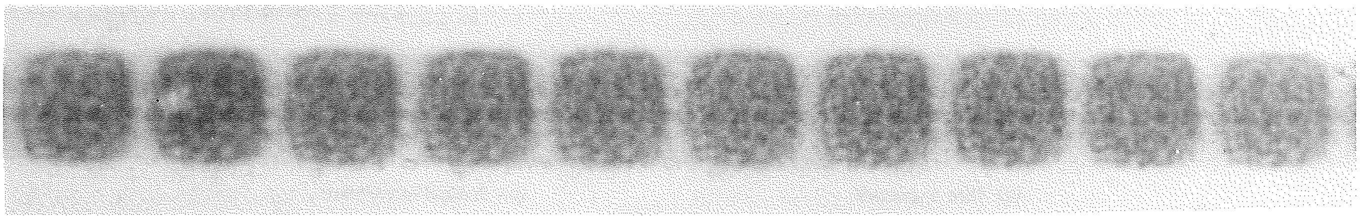
The laser mirrors required occasional adjustment to maintain the output power at a constant level.

The photographic recording film used throughout the tests was Agfa 10E56, with anti-halation backing, developed in Kodak D.19 for 4 minutes at 20°C with intermittent agitation. Typical exposures required for the film were 8 μJ/cm^2 (λ = 441 nm, exposure time = 500 ns).

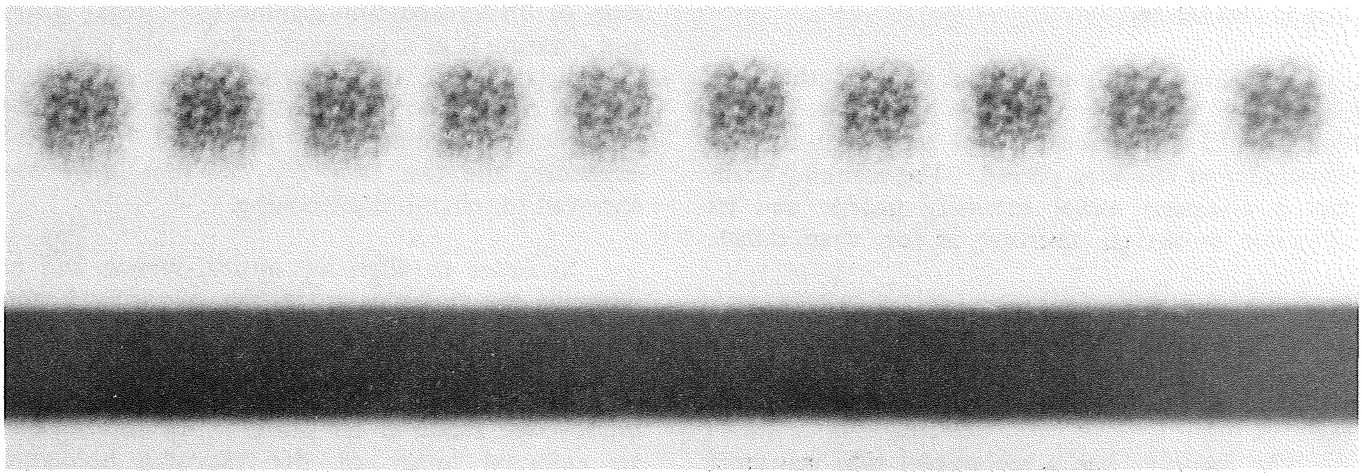
By altering the reflection-to-transmission ratio of the beam-splitting mirror, and by inserting attenuators in the reference beam, the ratio of the intensity of the reference-beam to the signal-beam at the recording plane could be adjusted from about 4:1 to 20:1.

3.2. One hologram per row

Most of the dynamic test recordings were made with only one hologram per row correctly exposed and with a reference-to-signal beam ratio of approximately 6:1. This was attempted initially by applying a repetitive pulse (500 ns wide) with a 64 μs period to a single stage of the



(*a*)



(*b*)

Fig. 4 - Tracks formed by recording one hologram per row
(a) using one deflection stage (b) using two stages in tandem

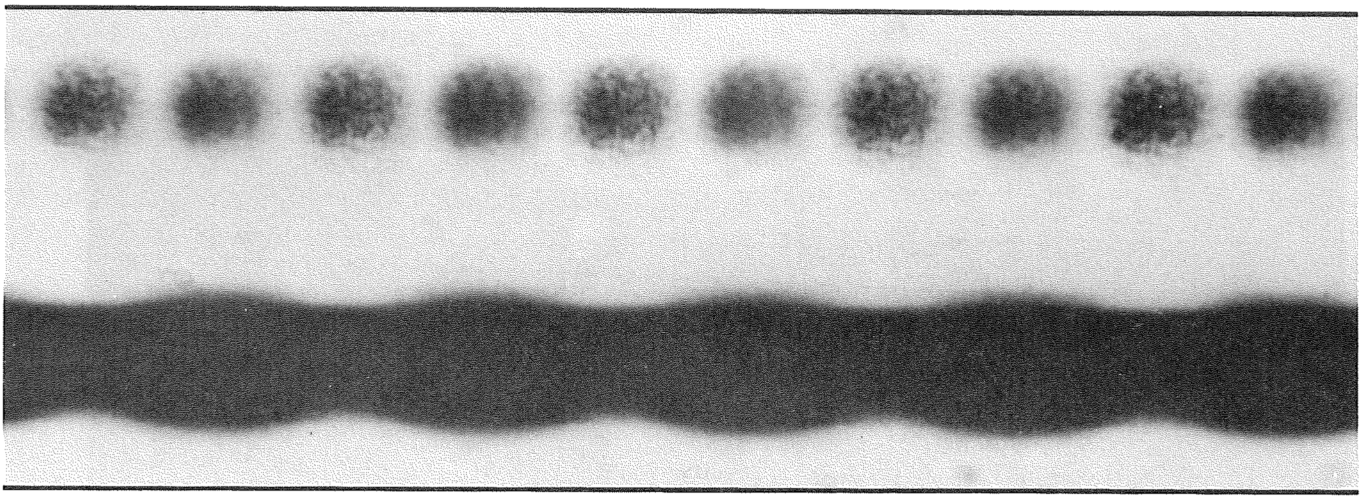


Fig. 5 - One-hologram-per-row recording with alternate holograms in the track only partly modulated (i.e. with 48 of the digit-beams 'off')

digital light-deflector and omitting the other stages. Photomicrographs of two typical track patterns are shown in Fig. 4. (The lower track in Fig. 4(*b*) and Fig. 5 is the rest position of the exposing hologram spot between deflection pulses and is, therefore, grossly over-exposed and blurred.) In Fig. 4(*a*) the holograms are clearly defined but the fine detail within them is not easily discernable and there is evidence of an inter-hologram background exposure. This was caused by incomplete switching of the deflector stage. Measurements of the optical switching waveforms showed that, by careful adjustment, an on/off extinction ratio of 100:1 could be achieved in the wanted hologram position. However, because of the low duty factor, even this degree of extinction was not sufficient to prevent an unwanted exposure occurring during the long 'off' period; the unwanted exposure was comparable in magnitude to the wanted exposure. The problem was overcome by inserting a second deflector stage in series with the first and switching it synchronously. This effectively improved the on/off extinction ratio to better than 1000:1 and substantially removed the inter-hologram background as can be seen in Fig. 4(*b*).

The principal aims of the test recordings made subsequently were:—

(a) to determine the effect on the hologram quality of the continuous motion of the film during the 500 ns exposure period.

(b) to optimise the recording parameters with respect to hologram diffraction efficiency, non-linear distortion and uniformity.

(c) to assess some of the impairments introduced by deficiencies in the principal transducers and the practical difficulties which might influence future developments.

(d) to provide rows of holograms for the assessment of the replay optics and the photodetectors constructed for data recovery.

The test holograms could be modulated using the page-composer. An example of this is shown in Fig. 5 where alternate holograms in the track had only 2 of the 50 digit-beams switched 'on' by the page-composer.

Although the outermost digit-beams in a reconstructed page were generally much weaker, as is described in Section 4.2.1, there was no evidence to indicate that those beams with a radial position in the direction of the film motion during recording were weaker than the other outermost ones. This suggests that the continuous motion of the film does not have any significant differential effect on the modulation transfer factors for the various digit-beams.

From the signal-beam switching waveforms of the exposing hologram spot, it was estimated that the on/off intensity ratio of the digit-beams was greater than 10:1, averaged over the 50 beams. This degree of contrast was also found in the reconstructions of the alternately modulated holograms and similar ratios were obtained, as described in Section 4.4.

3.3. Sixteen holograms per row

Four stages of the digital light-deflector were constructed to record a track of holograms with sixteen holograms per row. Fig. 6 is a photo-

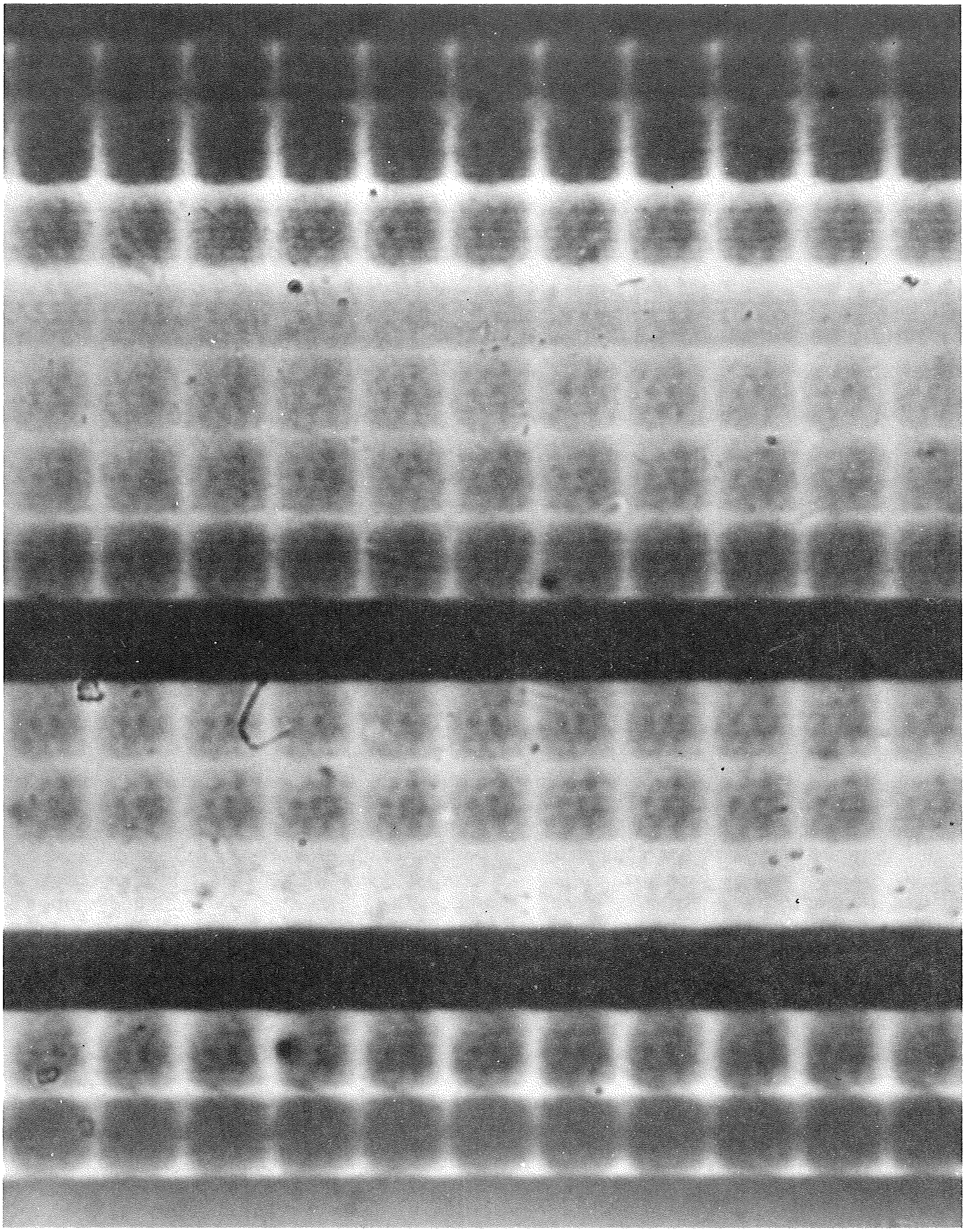


Fig. 6 - Recorded track with sixteen holograms per row. Film motion in direction left-to-right, deflection top-to-bottom

micrograph of a portion of a recorded track with sixteen holograms per row; the film motion is in a direction from left-to-right and the deflection from top-to-bottom. The sixteen holograms in each row were written consecutively in 8 μs and the beam returned to the start position (the extreme top position in Fig. 6) for the remainder of the 64 μs scan period. Because the laser was not switched off during this relatively long rest period, any unwanted stray images and flare-light, even if at low intensity compared with the wanted image, can produce the gross over-exposure effects seen by the black bands in the Figure; the over-exposure at the top is probably due to flare surrounding the rest position while the others are due to ghost images generated by the deflector with the beam at the rest position. These ghost images, at output positions other than the addressed position, arise from slight misalignments and misorientations of the electro-optic crystals within the deflector which can introduce small amounts of natural birefringence.

The intended purpose of these recordings was to study the effects of the limited switching efficiency of the polarisation switches in the deflector. For example, sufficient cross-talk between holograms might be introduced to reduce significantly the on/off contrast ratios of the reconstructed digit beams. Unfortunately, due to temporary problems with the page-composer,[5] hologram tracks suitable for assessing these limitations have not yet been recorded.

3.4. Practical difficulties

Apart from the drift in the optical line-up which was referred to earlier, it was found difficult to reduce the intensity of reflections from the surfaces of the various components sufficiently to prevent the recording being contaminated significantly by stray light. A critical area is the digital light-deflector which is constructed from many components, including electroded surfaces in the form of ladder grids which have a high reflectance. Ideally, the array of digit-beams and the reference-beam would pass unobstructed through the gaps in the electrodes, but any misregistration or scatter due to imperfections gives rise to multiple reflections and unwanted stray light. Further careful consideration will need to be given to the anti-reflection treatment of external surfaces and means for keeping the components clean, especially those near the recording plane.

The overall efficiency of the system relies on achieving a near diffraction-limited optical performance; thus lenses and mirrors, especially in the signal-beam path, where the numerical apertures are greater, need to be well-corrected and of good optical quality.

A further difficulty arose from the cumulative effects of small amounts of unwanted birefringence. These are introduced mainly by the imperfections in the page-composer and the digital light-deflector which contain electro-optic crystals, although some of the other components can contribute significantly. The He-Cd laser itself, for example, although nominally plane-polarised, was found to be slightly elliptically-polarised. These birefringent defects tend to reduce on/off contrast ratios and promote crosstalk between holograms.

4. Reconstruction experiments

Initially a single hologram was statically recorded using a simple multi-apertured plate instead of the page-composer, to generate the fifty digit-beams. A reference-to-signal beam intensity ratio of 6:1 was used in the recording as mentioned previously. This particular ratio was found experimentally to be optimum from a recording point of view when dealing with 50-bit holograms. Measured digit-beam power levels of 0.183 μW were achieved for digits near to the centre of the reconstructed page and with 1.45 mW incident on the hologram. This represents an effective holographic efficiency, defined as the ratio of the light power available from a digit-beam to the light power incident on the hologram, of 1.26×10^{-4}. For digit-beams near the edge of the page the holographic efficiency fell to 0.92×10^{-4}, which was consistent with estimates of the uniformity of the film characteristics from previous measurements.[1] This statically-recorded hologram was used as a reference standard for the analysis of the subsequent dynamic recordings.

Most of the replay experiments were carried out using dynamic recordings containing a single hologram per row and using the replay system arranged as shown in Fig. 7. Two of the test recordings were used predominantly and these are referred to here as A1 and A7. Both were recorded with nominal reference-to-signal-beam intensity ratios of 6:1 and with alternate holograms modulated 'on' and 'off' using the page-composer. These particular test recordings were used to ascertain the holographic efficiency which could be achieved with the page-composer operating and recording on moving film. The A7 recording had two separate tracks, one with

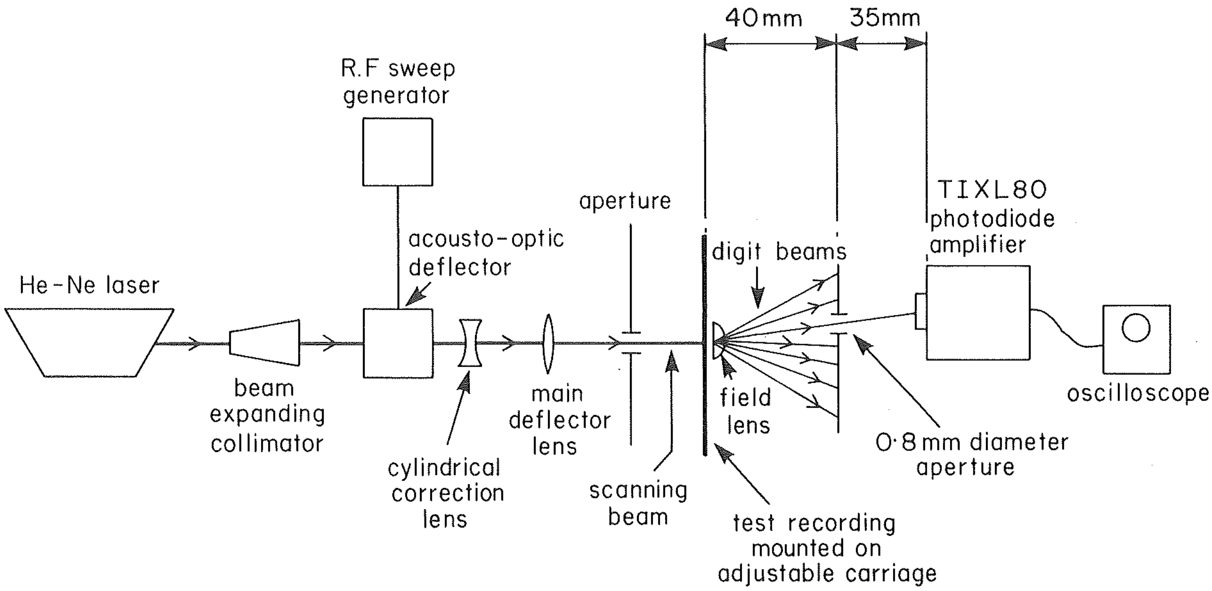


Fig. 7 - The replay system measuring arrangement

holograms separated by a guard band of 10 μm as proposed (Fig. 1) and the other with adjacent holograms just abutting each other (i.e. centres 50 μm apart). This latter arrangement allows the recorded film to be turned through 90° and placed in the replay head to simulate a complete row of holograms. Measurements were made on the holographic efficiency, the contrast-ratio between 'on' and 'off' digits, the optimum detection bandwidth and the resulting signal-to-noise ratio of the output signal. Also, the focusing and scan tolerances were noted. During the course of the experiments difficulties and problems arose which, together with the main results, are described in this Section.

4.1. Holographic efficiency

The following measurements of holographic efficiency are an average taken over more than 18 holograms and they apply to a digit-beam near to the centre of the data page. The acousto-optic deflector was omitted for these measurements.

A1 recording : 1.2×10^{-4}

A7 recording : 1.3×10^{-4}

It was found that a slightly smaller reconstruction spot-size than that estimated from theoretical considerations[4] gave better results; the optimum size was approximately 80% of the theoretical estimate and the spot appeared just to fill the hologram.

4.2. Digit-beam intensity variations

4.2.1. Variations within a hologram page

Fig. 8 shows a typical reconstruction of a hologram with all digit-beams 'on'. This photograph was taken by allowing the reconstructed hologram image to fall directly on a photographic film and with the strong central beam blocked to avoid flare effects.

The digit-beam powers from the reconstruction of a single hologram in the A1 recording were measured for a number of digit-beam positions

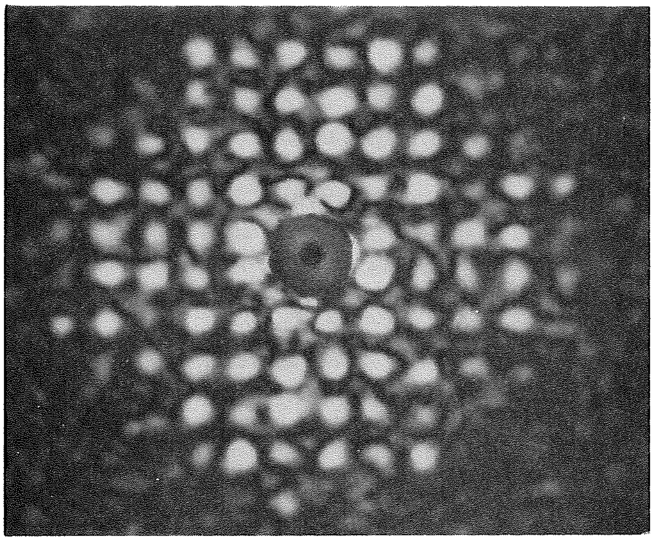


Fig. 8 - Reconstructed hologram with 50 digit-beams 'on'

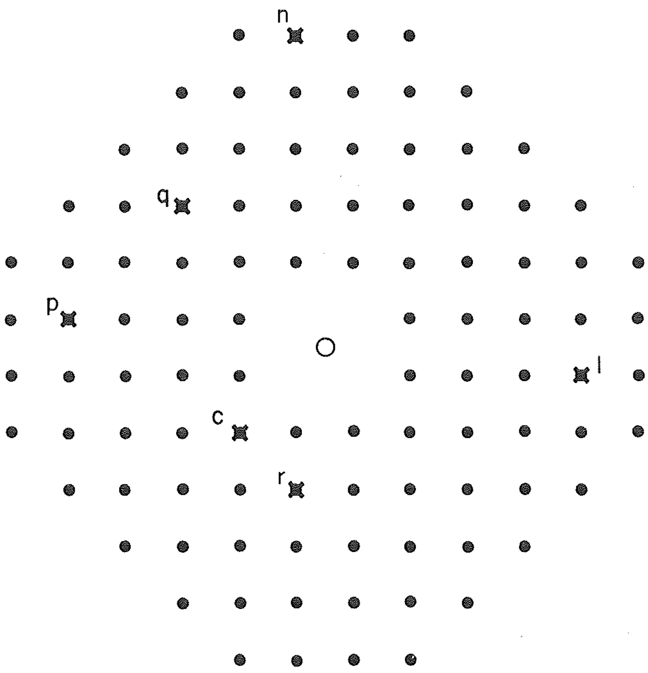


Fig. 9 - Digit-beam pattern in reconstructed data page (50 image pairs) showing marked locations for intensity measurements

● digit-beam ○ reference-beam

within the page. Referring to Fig. 9, which shows the complete pattern of digit-beams in a reconstructed hologram page, the chosen positions include a representative selection from the 50 pairs of digit-beams. The measured digit-beam powers and the corresponding holographic efficiencies are shown in Table 1.

From Table 1 it can be seen that the measured range of digit-beam powers within the reconstructed page is more than 5:1. Visual inspection of the reconstructions showed an irregular variation of digit-beam intensities within the page and a marked drop in intensity of the outermost digit-beams. Some of this non-uniformity can be attributed to unequal digit-beam intensities at the recording stage which are introduced principally by the page-composer. Further investigation is required, but it is possible that the irregular variations are caused partly by surface deformations of the film emulsion which are introduced in the processing. This effect is discussed more fully in the following Section.

4.2.2. Hologram-to-hologram variations

The results of intensity measurements at the same digit-beam location in the page often revealed quite unexpected variations, of up to 2:1, between those holograms in a sample which had nominally identical exposures. (See, for example, the variations of the upper peak values corresponding to the 'on' holograms in Fig. 10, which is described in Section 4.4.)

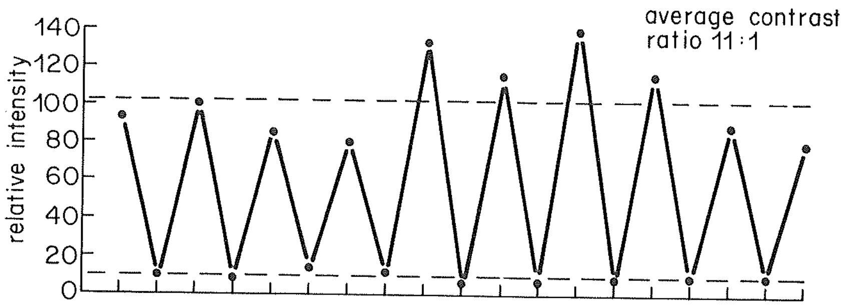
One possible reason for the hologram-to-hologram variations in the measured digit-beam powers could be that dust or scratches on the film emulsion accidentally distort the reconstruction of the affected holograms. However, in the examples which were investigated no evidence of any such gross defects could be found.

Another reason, which needs further exploration, is that the holograms may not be, as intended, pure amplitude holograms, but have an additional phase-component. This could be introduced by a relief pattern formed on the gelatin surface when the film is processed. Moreover, the phase-component could be unstable and perturb the wavefront phase-uniformity sufficiently to cause distortion of the diffraction process that controls reconstruction, which would otherwise be dominated by the wanted amplitude variations.

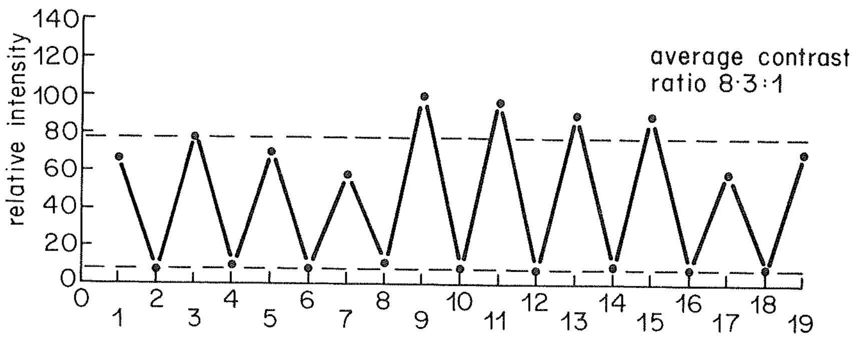
TABLE 1

Variation of digit-beam powers within a hologram page

Digit position (see Fig. 9)	Measured digit-beam power (μW)	Holographic efficiency
c	0.446	1.65×10^{-4}
r	0.411	1.52 "
p	0.268	0.99 "
q	0.223	0.83 "
l	0.183	0.68 "
n	0.085	0.31 "



(a)



(b)

Fig. 10 - Contrast ratio measurements without deflector in system
(a) spot size : 38 μm diameter (b) spot size : 46 μm diameter

4.3. Deflector distortions

The intensity variations within a hologram page were re-measured with the acousto-optic deflector present and the results are given in Table 2.

The results with the deflector installed, but not driven, reveal the level of wave-front distortion which the acousto-optic medium in the deflector introduced. Further results taken from a number of holograms in the row confirm that the holographic efficiency was reduced by between 20%

TABLE 2

Effect of the deflector on the measured digit-beam powers

Digit position (ref. Fig. 9)	Deflector installed but not driven		Deflected-beam used for reconstruction	
	Digit-beam power (μW)	% of value without deflector*	Digit-beam power (μW)	% of value without deflector*
c	0.321	72	0.096	22
r	0.348	85	0.092	22
p	0.183	67	0.064	24
q	0.201	90	0.069	31
n	0.055	65	0.023	27

* The results in these columns have been corrected for a small loss in transmission obtained with the deflector installed.

and 30% when the deflector was inserted. It was found that the holographic efficiency could be optimised by adjusting the lateral position of the deflector with respect to the incident beam (without disturbing the setting of the Bragg angle[2]).

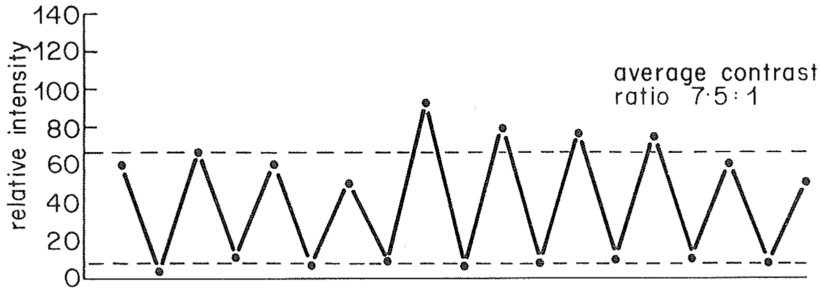
The results obtained with the deflected beam interrogating the hologram, shown on the right-hand side of Table 2, were taken with the deflector driven at the maximum r.f. power level which caused no spurious beams to be generated within the scan range. Also, by driving the deflector at a continuous r.f. frequency the deflected beam was held stationary in the middle of its full deflection range. Again, further measurements averaged over several holograms indicated an effective deflector efficiency of 23–27% overall. This poor overall efficiency relates to the particular deflector (which was an early model) used for the experiment, and is not typical of modern deflectors now commercially available.

4.4. Contrast ratio

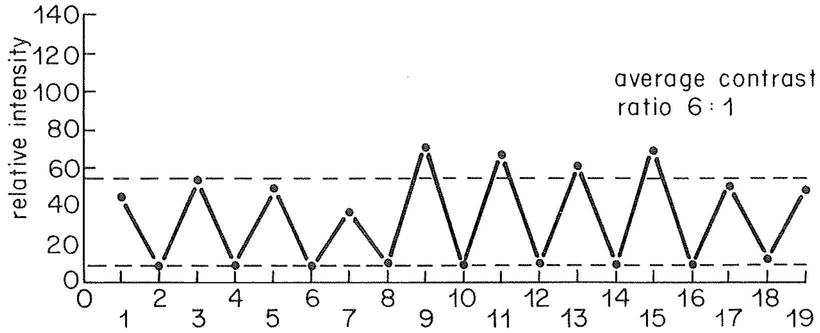
4.4.1. Manual scanning

The replay optics were set up with the A1 recording mounted on a carriage which could be positioned accurately. This allowed a stationary reconstructing beam to 'scan' along a 'row' of holograms, one by one, by manual control of the film carriage. By manual scanning, the effects of rapid deflection and photodetector-bandwidth limitations were eliminated. The results shown in Figs. 10 and 11 are the relative digit-beam powers measured along the same group of alternately modulated holograms, using the 60 μm spaced holograms. Two reconstruction-spot sizes were used and the results in Figs. 10 and 11 are without and with the deflector installed, respectively. The amplifier following the photodetector was d.c. coupled so that the 'off' level measured was a true indication of the background light level. To isolate and measure a selected digit-beam, a 0.8 mm diameter aperture was placed at an image distance of approximately 40 mm from the film, as shown in Fig. 7.

From the modulation performance of the page-composer in the recorder, on/off contrast ratios better than 10:1 were expected in the reconstruction and the results without the deflector installed show that, with the optimum spot size, this was achieved, on average. The deflector unfortunately degraded the contrast-ratio in the replay process, although during this



(*a*)



(*b*)

Fig. 11 - Contrast ratio measurements with deflector in system

(a) spot size : 38 μm diameter (b) spot size : 46 μm diameter

particular experiment the lateral positioning of the deflector may not have been optimum. Later measurements showed that the contrast-ratio was reduced by less than 20% with the deflector included in a favourable position. Occasionally, an abnormally high value of digit-beam power was measured but this was usually due to flare resulting from dirt on the field lens and/or prism, or a scratch on the film emulsion or backing.

4.4.2. Scanning at television line rate

For these tests, the replay optics were assembled onto a purpose-built optical bench which can be located in an upright position beneath the deck of the recording equipment. On this bench a right-angled prism is used between the deflector lens and the film to allow the replay scanning beam to address the film in the required direction.[4]

With the correct r.f. drive applied to the acousto-optic deflector (i.e. with the r.f. carrier frequency modulated by a linear ramp at television line frequency), the deflection range was sufficient to scan more than 20 hologram positions satisfactorily. Fig. 12 is an oscilloscope display of the photodetector output from a scan of alternately modulated holograms with a spot size slightly larger than optimum. At this stage, the cylindrical corrector lens following the deflector was set for maximum signal excursion. The measured contrast ratio is found to be reduced to 5.6:1. The main loss in contrast is believed to be due to

(a) the introduction of beam-profile distortion and flare by the deflector and its corrector lens;

(b) the non-uniform frequency-response of the low-pass filter following the photodetector amplifier.

A numerical analysis of these effects is given in Section 4.8.

4.5. Detection bandwidth and signal-to-noise ratio

Assuming a 50% probability that successive bits are of opposite sign, as with a random-noise signal output, a 2 Mbit/s , NRZ data stream has an average of 10^6 transitions in level per second. For a television signal, the probability is typically lower than 50%[2].

Several low-pass filters with various bandwidths were inserted in turn after the photodiode amplifier in order to define and optimise the noise bandwidth of the detection system. Using a digit-beam near the page-centre of the A7 recording, the variation of the measured signal-to-noise ratios with detector bandwidth is given in Fig. 13. A digit-beam power of 0.04 μW was incident on the photodiode.

It is reasonable to suppose that the optimum bandwidth for signal decoding should be between 1 MHz and 2 MHz; this can be finally established only when recorded television data is available

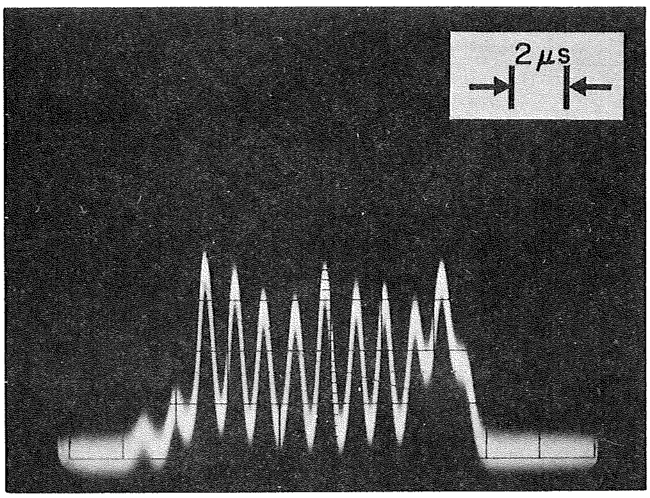


Fig. 12 - Oscilloscope trace showing the output at one digit-beam location of a row of holograms, spaced 60 μm apart and alternately modulated, when scanned at television line rate. TIXL 80 photodetector amplifier used

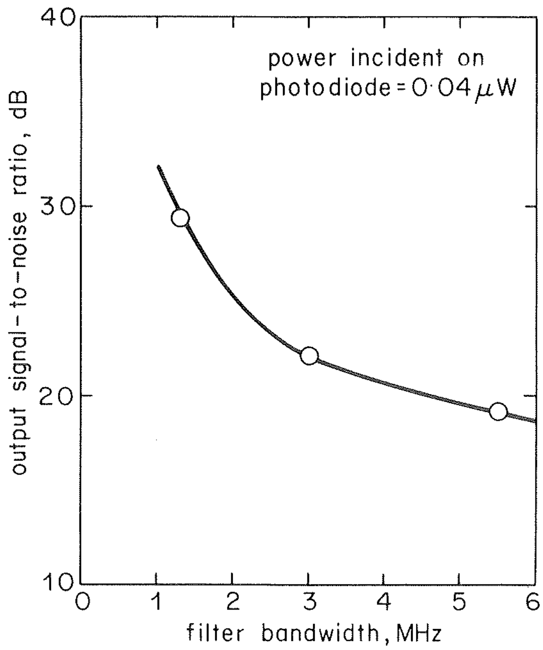


Fig. 13 - Measured signal-to-noise ratio as a function of detector bandwidth

for analysis. However, in the meantime, a simple filter was designed which contains only 5 components; it has a Butterworth type of frequency response and a cut-off frequency at 1.3 MHz.[5] The measured insertion loss at 1 MHz is −1.5 dB. Because 50 such units are required for the complete array, it is desirable to keep the filter simple and inexpensive.

The results of Fig. 13 show that signal-to-noise ratios approaching 30 dB are possible with the present levels of power obtained in the reconstructed digit-beams.

4.6. Focus and scan tolerances

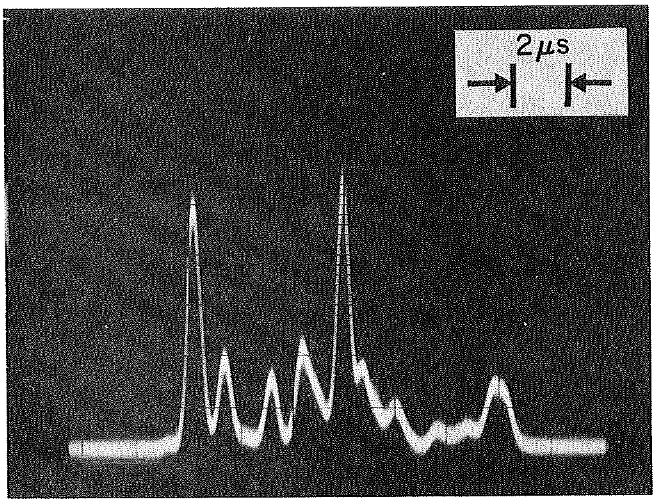
Focus tolerances were expected to be quite large because of the small numerical aperture of the replay scanning beam. Measurements indicate that an axial movement of the deflector lens of ±0.75 mm gives rise to a 1 dB loss of recovered digit-beam signal. This tolerance is amply sufficient to accommodate film movement in the replay-head gate normal to the plane of the film.

The effect of laterally positioning the scanning-beam off the centre of the hologram was also examined. A misregistration of up to half a hologram (±25 μm) gave a 6 dB digit-beam signal loss, as expected, when the adjacent row was unoccupied. This tolerance reduces to ±15 μm when the adjacent row is occupied. It is estimated that an auxiliary servo system[4] will need to maintain the scanning-beam centred on a row of holograms to better than ±10 μm.

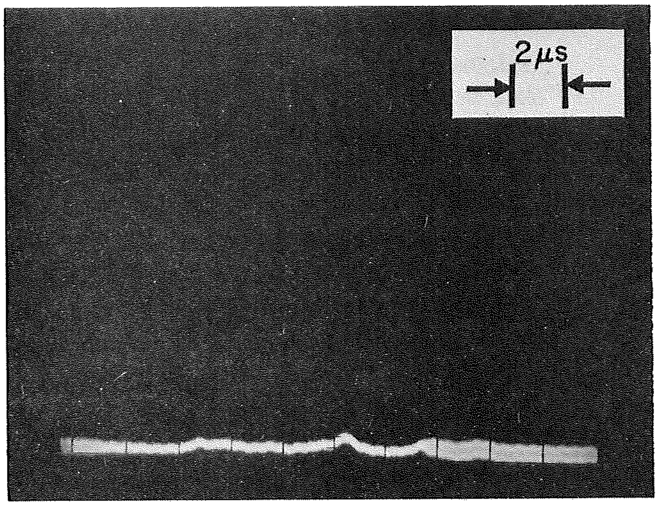
4.7. Surface dirt and scratches

The cleanliness of both the field lens and the right-angle prism, which are located near to the film, is very important. The effect of flare resulting from a dirty field lens is illustrated in Fig. 14, where oscilloscope traces of the detector output during a scan with the film omitted were recorded before cleaning in Fig. 14(*a*) and after cleaning in Fig. 14(*b*).

Scratches and dirt on the film also cause similar flare effects; severe scratches can cause the complete loss of data from a hologram and this could only be tolerated occasionally. The long-term effects of surface contamination will not be known until error rates can be measured with moving film and real data in a fully operational environment. Dirt on the film can be removed by a strict cleaning process prior to it reaching the replay head; air brushes would be applicable here, but they may not be sufficient alone.



(*a*)



(*b*)

Fig. 14 - The amplified photodetector response at a digit-beam position without the film
(a) before cleaning the right-angle prism and field lens
(b) after cleaning

4.8. Replay performance

It is perhaps useful to show some of the results obtained while measuring the reconstruction efficiency of the A7 hologram recording, in order to summarise the deficiencies of the present replay system. Using the holograms spaced 50 μm apart and a detector preceded by a 0.8 mm diameter aperture (see Fig. 7), the results shown in Table 3 were obtained for a typical digit-beam in the middle of the data page.

The last row of results was obtained using a monofilament, optical fibre light-guide (nominally 0.76 mm diameter) between the detection plane and the photodiode. The overall loss in digit-beam power between the manual scan (with

TABLE 3

Some measurements of replay performance

	Digit-beam power with an 'on' hologram (μW)	Digit-beam power with an 'off' hologram (μW)	Effective holographic efficiency	Contrast ratio on/off
Manual scan : no deflector	0.303	0.038	0.77×10^{-4}	8 : 1
Manual scan : deflector in but not driven	0.238	0.034	0.63 "	7 : 1
Manual scan : deflected beam	0.076	0.013	0.59 "	6 : 1
Television line-rate scan	0.042	0.007	—	6 : 1

deflected beam) and the scan at line rate was about 5 dB. This total loss may be apportioned as follows:—

(a) loss in monofilament light guide including interface losses — 3.5 dB

(b) low-pass filter insertion loss at 1 MHz — 1.5 dB

Total — 5.0 dB

The oscilloscope trace of the photodetector output after amplification and filtering is shown in Fig. 15 for a group of alternately-modulated holograms scanned at television line rate. The average signal excursion is equivalent to a digit-beam power difference of 0.035 μW which when compared with a measured r.m.s. noise level equivalent to 1.25 pW gives a signal-to-noise ratio of 29 dB. In a page, some of the digit-beams with lower powers will produce signal-to-noise ratios possibly up to 10 dB worse than this.

In the final system, two optical fibres will be used (one from each of the twin image positions*) and their photodetector output signals combined before amplification. This is expected to increase the signal-to-noise ratio by at least 3 dB.

* In a hologram reconstruction, which is an optical diffraction process, each bit of information in the recorded hologram gives rise to a pair of diffracted digit-beams (the ±1st order components) symmetrically disposed about the direction of the incident (reconstructing) beam. This pair produces 'twin' images at the detection plane and one or both of them can be intercepted and used for detection.

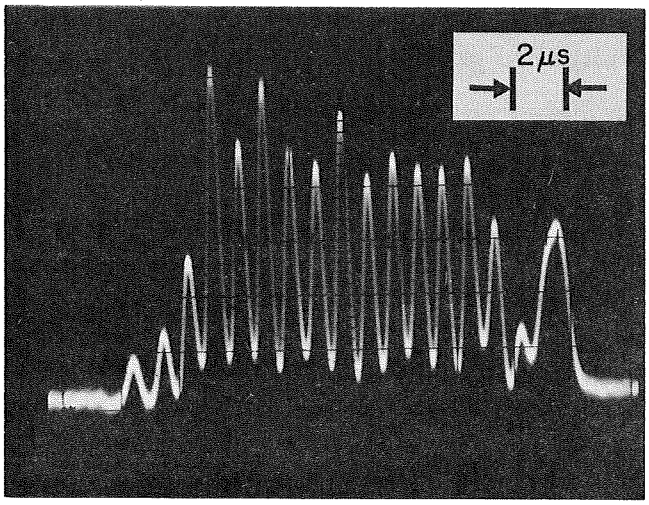


Fig. 15 - Oscilloscope trace showing the output at one digit-beam location of a row of holograms spaced 50 μm apart and alternately modulated when scanned at television line rate. Monofilament light guide and IPL 33 photodetector amplifier used

4.9. Hologram deterioration

A disturbing side-effect of the replay investigations was an apparent deterioration and vulnerability of the recorded holograms. Diffraction efficiencies measured on freshly recorded film were not always repeatable and the reconstructed image appeared on occasions to become progressively distorted, with more intermodulation products appearing between the expected digit-beam locations. In one instance, a measured digit-beam intensity of 0.52 μW initially fell to 0.22 μW — a loss of 58%!

The precise reason for the deterioration is unknown but it is suspected that the recorded hologram (ideally a thin amplitude-hologram) contains an unstable additional phase component which affects the reconstruction. This is the same reason as that suggested previously in connection with the hologram-to-hologram intensity variations. A surface variation in the emulsion of the film has been measured, using interferometric techniques, to be about 200 nm (peak-to-trough) maximum at a hologram location. This corresponds to about 114° differential phase excursion at 633 nm wavelength. An attempt to index-match a deteriorated hologram, by sandwiching the film in silicone oil between two glass slides, partially restored the image quality and the measured digit-beam powers were within 71% of the original levels.

5. Conclusions

Thus far, a proper test of the system feasibility has not been achieved and the digital recording and replay of part of a television picture has not yet been demonstrated. However, dynamic test recordings have been made on photographic film and these have been carefully analysed.

The basic system concepts appear to be fundamentally correct, and the experimental transducers have come very close to meeting the bandwidths necessary to handle an overall data transfer rate of 100 Mbit/s.

The holographic efficiency in the reconstruction of the dynamically recorded holograms compares favourably, for digit-beams near the centre of the page, with previous recordings obtained with the film stationary. The efficiency of the outermost digit-beams in the page-composer is significantly lower with moving film but there is no evidence of any differential blurring in the hologram due to the continuous film motion in one direction during exposure.

The reconstructed image quality was good with very little distortion in virgin recordings, but the uniformity of digit-beam powers within the page was generally poor and there were inexplicable variations ($\simeq$ 2:1) from hologram-to-hologram at a given digit-beam location. Perhaps the most disturbing feature was that some of the samples which were repeatedly measured appeared to 'age' and the image quality deteriorated quite drastically on occasions. There is some evidence that this hologram non-uniformity and deterioration is associated with unwanted surface-relief patterns at the hologram locations, which are induced in the gelatin matrix of the emulsion during the chemical processing.

There is a wide latitude in the replay system for focus and scan errors. The focus tolerance in recording is smaller but can be met without difficulty.

As expected, flare due to dirt and surface contamination is a problem in both recording and replay equipment. Sensitive areas are the surfaces of optical components near the film plane, such as the field lens in the replay apparatus and the digital light-deflector in the recorder.

The method adopted for detecting the digit-beams, using monofilament light-guides coupled to discrete photodiodes, gave satisfactory results. Data was recovered at the required rate with detector signal-to-noise ratios better than 26 dB after amplification and simple low-pass filtering, notwithstanding the poor optical efficiency (25%) of the particular acousto-optic deflector used for the reconstruction experiments.

The tests indicated that the efficiency of hologram reconstruction is sensitive to any wave-front aberrations in the reconstructing laser beam. A smooth (Gaussian) radial intensity profile gave the best results, but the correct size of spot should be ascertained experimentally.

6. Recommendations for future work

The results have highlighted some critical areas where more investigation is required, in particular with regard to problems associated with the film and its processing. A clearer understanding of the influence of surface deformations of the film on hologram image quality, and of the physical conditions which generate and change the deformations is needed. Completion of the partially-populated recorder has now been suspended until ways of mitigating the film problems are found.

Improvements in the quality of some of the optical components used in the recorder would enable the page uniformity and the holographic efficiency of the recordings to be increased. Also, a better acousto-optic deflector in the replay system is required.

Further consideration should be given to the treatment of component surfaces and to methods of maintaining surface cleanliness so

that flare effects are kept to a minimum.

Given some improvements in these areas, the next experiment should be to recover data from moving film and assess the overall error rates using diagnostic input signals.

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